Historical sources and watershed evolution

BY STANLEY W. TRIMBLE*
Department of Geography, University of California, Los Angeles,
CA 90024-1524, USA

Historical data, including structures, documents, photographs and eyewitness reports, allow changes in some drainage basins to be documented in fine detail over time periods ranging from a few days to several decades. The USA is rich in data sources that are freely available. Rates of bank erosion, meander migration, channel width, riparian vegetation and watershed land use and cover conditions can be assessed, which are especially valuable where there is controversy over the human contribution to erosion and deposition. Studies of Coon Creek and the southern Piedmont of the USA have yielded results that sometimes contradict established views.

Keywords: aerial photographs; cadastral maps; watershed evolution; Piedmont; Coon Creek

1. Introduction

The use of historical sources in geomorphology is not new, witness the work of Gilbert [1], Happ et al. [2] and Vita-Finzi [3], the recent review of landscape reconstructions by Whitney [4], and the methodological papers on this topic that have appeared in the last quarter of a century, including those by Thornes & Brunsden [5], Hooke & Kain [6], Gregory [7], Cooke & Doornkamp [8], Trimble & Cooke [9], Collins & Montgomery [10], Egan & Howell [11], Brown et al. [12], Gurnell et al. [13] and Trimble [14].

The present paper focuses on drainage basin evolution, and it outlines the main bodies of historical evidence on which we can draw. The case studies are from the southeastern and midwestern USA, regions that are well endowed with the necessary geological and documentary sources and which demonstrate the importance of a historical perspective, especially where the progress of watershed erosion and aggradation has been disputed or misinterpreted. The concluding section considers the significance of river history in the context of river remediation, that is to say where the past is the key to the future.

2. Documents and structures

Written accounts take two basic forms. The first is a description of past events or changes, while the second is the description of contemporary or baseline conditions useful for later comparisons. Evidently, one needs to consider the

*trimble@geog.ucla.edu

One contribution of 10 to a Theme Issue ‘River history’.
scientific credentials of the observer, and the stage of scientific development at the time of observation; thus, a nineteenth century document may attribute an erratic to transport by the Biblical flood. Accounts from scientific observers tend to be dependable and are often extremely helpful, especially when they relate to direct observations such as the clarity of streams. Other accounts may need more qualification or interpretation. Somewhat less valuable sources are contemporary newspapers, periodicals, books, government records and unpublished manuscripts.

Climatic records, especially if kept regularly by governmental agencies, are often of exceptional value to stream studies. Figure 1 shows an example of precipitation data for the Driftless Area in the Upper Midwest, together with some analyses (US Weather Bureau data: [15]). In the US, official climate records sometimes go back to the mid-nineteenth century, but scattered observations were made earlier. Individual storms may prove to have had significant geomorphological effects.

Stream discharge data for the US extend to about 1850, are quite plentiful for this century, and are generally accessible on the Internet. Suspended sediment data are available for certain streams, starting as early as about 1905. Websites for various agencies with data on water quality and quantity are given in Ward & Trimble [16]. In the UK, Ordnance Survey topographic maps record the long-term evolution of British streams and basins [6]. Land use from 1776 was reconstructed from such maps by Foster & Lees [17], and channel changes have been studied by among others, Petts [18]. For the UK and the rest of Europe, discharge data are less plentiful and generally date from the early to the mid-twentieth century.

Land use is, of course, a major causal factor in stream change, and its changing character needs to be correlated with contemporaneous geomorphic phenomena in model building. In this task, agricultural census data may prove disappointing because categories and definitions often change from one census to the next. For the US county, enumerations are for ‘land in farms’ only and sometimes cover only fractional parts of counties; the census manuscripts give far more detailed information than the published reports. The area of enumeration units may also change with time and need to be reconstructed [19].

Information on changes in land use can also assist the stream restoration designer in ensuring that a proper analogue is selected. The changes may be gradual, abrupt or seemingly episodic over time, depending on climate fluctuations, population movements and shifts in agricultural commodity markets. Though only planimetric, land surveys can prove highly informative in fluvial reconstructions. The original US land surveys sometimes make it possible to establish pre-agricultural floodplain conditions, upland vegetation and stream widths. Other sources of information include photographs and maps, written references and reports, people with long-time knowledge of the area, highway and railway bridge data, and field evidence. They may yield estimates of the river’s longitudinal profile and cross section and thus contribute to palaeohydrological analysis and the development of a template for restoration work.

Where a channel has been substantially modified from its historic condition (say by being channelized), or has been artificially relocated, natural surface topographic features, soil distribution and vegetation patterns may help to characterize the historic stream by revealing relict channel sections, cut banks,
Figure 1. Precipitation time trends in the Driftless Area of the Upper Midwest, 1867–1974. The sigma notation denotes 1 standard deviation from the mean. (a) Number of weather stations; (b) average annual precipitation and time trends; (c) relation of annual precipitation and storms exceeding 2.5 inches (63.5mm) in 24h and (d) 3 year moving average annual precipitation. Reproduced from Trimble & Lund [15].

Figure 1. Precipitation time trends in the Driftless Area of the Upper Midwest, 1867–1974. The sigma notation denotes 1 standard deviation from the mean. (a) Number of weather stations; (b) average annual precipitation and time trends; (c) relation of annual precipitation and storms exceeding 2.5 inches (63.5mm) in 24h and (d) 3 year moving average annual precipitation. Reproduced from Trimble & Lund [15].

levees, stream terraces and floodplain wetlands. Careful timing of the fieldwork or inspection from the air is sometimes essential, especially where seasonal moisture or subtle morphologies are critical to the diagnosis. Cultural features
with documented locations, such as bridge supports and streambank stabilization structures, provide field evidence of the former position of the stream channel and bank. In urbanized areas, gravity-fed sewer system pipes and manholes typically follow stream valleys, and exposure of buried sections may provide clear evidence of shifts in the position of the stream or of downcutting. But if it is clear from other evidence that conditions within the watershed condition have changed substantially over time, the cultural evidence may be compromised and its possible influence on channel evolution will need to be assessed.

Litter, including mobile artefacts such as tools, vehicle parts, bottles, cans, package wrappers and any other datable artefacts, may be precisely dated, but its location can only give a maximum age for overlying deposits. For example, a beer can made in 1939 may have been dumped into a stream in 1950 where in 1952 it was buried in a point bar, which was eroded away in 1960 so that the can came to be buried 20 cm deep on a downstream floodplain. The only safe conclusion is that there has been a minimum accretion of 20 cm at the final location since 1939. However, finding several items at similar levels with similar dates might allow a stronger inference, as when an intact dump is located in a floodplain.

Various artificial structures, including bridges, dams, mills, reservoirs, fords and fish traps, roads, canals, causeways and buildings, can serve as gauges to assist in measuring fluvial change. Inspection of older bridges by a practised eye can yield immediate information about stream processes. Aggrading streams are often indicated by reduced stream openings and by the burial of structural members (e.g. wing walls) that are usually exposed to the stream (figure 2). Degrading streams, on the other hand, can often be diagnosed by old water lines left on structural members, by exceptionally large openings, and by the exposure of structural members, such as footings and pilings, which are usually placed beneath the surface. Figure 3 shows changes in stream morphology based on comparison of bridge plans with new survey data [20,21].

Bridge plans are even more useful, as they will usually include a stream and a valley cross section surveyed before bridge construction, which can be resurveyed.
for comparison. One must of course ensure that the present bridge has not induced local scour or deposition. The plans may include a detailed topographic map of the stream reach and perhaps also surveyed cross sections at some distance upstream or downstream, particularly valuable because they are less affected by scour effects induced by the bridge. At some sites, there may be traces of several successive bridges. Highway bridge plans in the US often go back to the early twentieth century and railway plans to the mid- to late nineteenth century. Fortunately, the same vertical datum is normally used for successive bridges at a site, so that resurveys of century-old profiles are simplified. Even when datum has changed, however, excavation may reveal in part the changes in question. Bridges are usually inspected periodically by government agencies, and the resulting reports are likely to contain substantial descriptions, measurements and photographs, which can be used for time-lapse studies.

Changes in streams often create severe problems in the operations of dams, mills and reservoirs, and such problems may have been documented or can be established. While nearly all water-powered mills had reservoirs, most of these were channel-type pools that had very low trap efficiency for sediment. Fortunately, some mills, and later hydroelectric and flood-control dams, have a large volumetric capacity in relation to their drainage area, and thus a high trap efficiency, so that sediment yield can be measured with some confidence.

These data have the advantage of spanning long periods and bear components of the river’s sediment load (such as bedload) that are not generally gauged, but lake sedimentation rates may be inflated by the products of shoreline erosion. Many reservoirs are regularly surveyed, and the data are periodically
Figure 4. Headwater erosion rates based on sediment accumulation behind a small dam, Vernon County, Wisconsin, 1936–1977. Reproduced from Trimble & Lund [15].

published, usually by governmental agencies [22], but perhaps because reservoir sedimentation in the USA is now considered to be less serious than formerly, these records are now rarely updated. Figure 4 shows a series of detailed surveys of sediment accumulated over time behind a gully-plug dam in Wisconsin [15],
and figure 5 shows the variability in sediment production rates in watersheds in the Tennessee River Basin [23]. In the UK, there has been considerable work on reservoir sedimentation over the past few decades [24]. A neglected source of data going back to the mid-1700s is estate lakes, such as those built by ‘Capability’ Brown and Humphry Repton. Many estates have remarkably full records, some going back over two centuries.

Roads, railways and causeways serve as benchmarks to measure changes of stream morphology and processes such as lateral movement of streams or gullies. When the location of a road or canal in relation to the stream can be determined from documentary evidence, such as old maps or aerial photographs, its present location will evidently allow an average rate of lateral migration to be calculated. Authorities usually take whatever measures are necessary to protect a road or canal threatened by a laterally migrating stream, and some sort of documentation is normally prepared, often including plans and maps. Other road protection structures useful for later measurement are dikes, levees and rip-rap. Additionally, roads are often raised above normal flooding or aggrading floodplains by fill, and the level of the old road beneath may be ascertained from construction plans, borings or excavations.

Except for occasional mills, industrial buildings are rarely constructed on active floodplains, and even when close to streams, they are usually sited on river terraces. Thus, when a structure is affected by sedimentation, it indicates

**Figure 5.** Sediment yields for the Tennessee River Basin ca 1940–1975, based on Tennessee Valley Authority reservoir surveys. Reproduced from Trimble & Carey [23].

*Phil. Trans. R. Soc. A* (2012)
important changes of stream or sediment regime. Generally, when a building is significantly impacted by water, sediment or both steps are taken to move or raise the building if possible. If not, the building is usually dismantled, leaving only the foundation(s), which itself can serve as a benchmark. Once the foundations have been covered with sediment, however, the location must be established from old maps, photographs, land plans, eyewitness testimony or perhaps subsurface radar. Likewise, the chronology must be established from such sources as maps and cadastral maps, tax records or eyewitness accounts. Unlike roads and causeways, which may be located by borings, it is best to excavate around as much of the building as possible to see how it was related to the stream. Steps, walks, fences and small outbuildings would imply that the area was frequented by people at one time, thus implying low frequency of flooding. Buildings may be occasionally useful for measuring stream channel erosion.

3. Maps and photographs

Historical maps can be an invaluable source of site-specific information to characterize past stream conditions. Historical maps are housed in many different collections, including libraries and historical societies, as well as local, state and Federal government agency offices. For many areas of the United States, US Geological Survey (USGS) maps are the oldest accurate maps available. USGS maps date from 1879 when systematic mapping of the country was begun in the West. Websites of the USGS, National Archives and Library of Congress are particularly valuable sources for locating older maps. The USGS website also contains information on mapping standards. Information on past stream conditions that can be derived from historic maps is limited by map scale, accuracy of original survey work and climatic controls on stream character. In many areas, USGS topographic maps are often the largest scale historic maps available. Because USGS topographic maps are produced at infrequent intervals, only very long-term trends can be determined. This may prevent a detailed understanding of the effects of short-term physical processes and stream morphological responses.

Before the advent of aerial photography, streams were sketched in the field. The USGS generally mapped streams when water levels were at a normal stage. The sketching of shorelines of broad rivers, however, was a perplexing problem owing to periodic fluctuations in width. Riparian vegetation and other features also reduced map accuracy, depending on the date of observation. USGS map accuracy improved with the use of aerial photography beginning in the 1930s. Map accuracy further improved following the establishment of national accuracy standards in the 1940s and of better horizontal control features in the 1950s. Currently proposed standards require that definite streams be depicted within 0.02 map inches (40 ft (12.2 m) at 1:24000 scale) of their horizontal position.

The mapped accuracy of stream width by the USGS also depends on mapping conventions related to stream width. Before 1954, USGS maps depict streams as double lined only when actual width could be displayed without exaggeration. In 1954, the USGS adopted a standard, whereby the minimum stream width required for depiction using double lines on a map was 40 feet (12.2 m) for 7.5 min maps and 80 feet (24.4 m) for 15 min maps. These criteria had probably been widely
used for several years beforehand. In 1993, the minimum width requirement for a stream to be depicted as a double line on 7.5 min maps was increased to 50 feet (15.2 m). Streams narrower than this width criterion are depicted as single lines. On USGS maps from the 1800s through to the 1950s, streams mapped as single lines were depicted as tapering to become narrower towards the headwaters, and small side tributaries were depicted using a smaller weight single line than the main stream. These were conventions rather than measurements. From the 1950s onwards, all streams too narrow to meet the double-line width criterion were depicted as single, uniform blue lines, regardless of their actual width, and it is therefore impossible to derive stream width from current or past USGS maps. Additional difficulties arise where there is insufficient space to depict an engineered structure, such as a road or railway and an adjoining natural feature, as mapmakers tend to displace the natural feature, and in arid regions, where the location of channels is blurred by infrequent flow.

Early USGS maps can provide only limited information on profile changes. National map accuracy standards established in the 1940s require that 90 per cent of tested elevations on all USGS contour maps on all publication scales lie within one-half of the mapped contour interval; currently proposed standards require that definite streams be depicted within one-half of a contour interval of their vertical position. In mountainous regions, the wide footage between contours generally limits the ability to detect changes in stream elevation and longitudinal profile. In flat areas, the great lateral distance between contours limits the ability to determine elevation changes accurately, although the potential error is inherently much smaller.

Historic survey maps and associated notes can also be valuable sources of information. As streams were important resources to property owners, and creeks and rivers often form property boundaries, valuable information on stream condition may well be recorded in property surveys. Local governments, libraries and local historical societies may also have historic property survey information. Surveys conducted in association with construction of structures over and along a stream by private individuals, commercial enterprises and government agencies are of particular value. Government agencies involved in streamside projects potentially include highway departments, water supply and sanitary sewer agencies, the US Department of Agriculture, the Natural Resources Conservation Service, the US Department of Interior, the Bureau of Land Management and the US Army Corps of Engineers (USACE). Figure 6 illustrates how old land-survey maps and information can shed light on changed conditions [20,21]; owing to stream aggradation, the area noted as good land in 1785 was swamp by the twentieth century.

Analysis of the current condition evidently requires good map coverage. Geomorphologists working in the USA can access general topographic maps, created mostly by the USGS, which have been available for more than 100 years; a number of precise river surveys, usually by the USACE; detailed maps of coastal areas including stream and estuaries with bathymetry, usually by the US Coast and Geodetic Survey; stream stage-discharge studies by the USGS; and flood studies by various agencies.

The first aerial photographs available date from the 1800s, when photographs were taken from balloons and kites. Geographical coverage by these photographs, however, is very limited. Aerial photography became widely practised in the
1930s. The Library of Congress maintains a collection of aerial photographs taken between the early 1900s and the 1940s. Photographs taken by Federal agencies from the 1930s to the 1940s for mapping purposes cover approximately 80 per cent of the area of the lower 48 states and are available through the National Archives. The USGS maintains a collection of aerial photographs taken since the 1940s; aerial photography dating from the 1950s is available from the US Department of Agriculture Aerial Photography Field Office. High-quality aerial photographs are taken of nearly the entire country every 5–7 years by the National Aerial Photography Programme.

Figure 7 shows dramatic watershed land-use changes and changes in streams and drainage patterns between 1934 and 1967 [15]. Note the rectangular fields in the old system and the contour strip farming in the new. Note also the great decrease of drainage density resulting from better land use and decreased overland flow. Owing to the great number of factors affecting the resolution of aerial photographs, there is no rule of thumb guiding the minimum linear dimension that can be resolved on historic aerial photographs. Major factors influencing aerial photograph resolution include atmospheric conditions, ground conditions, aircraft movement, lens character, film character, camera height, camera position with respect to the Earth’s surface, camera quality and whether the film was black and white or colour. For the USGS, camera height was determined primarily by the desire to compile contours accurately for mapmaking. If the height was appropriate for contour mapping, it was generally good enough to map planimetric features including streams. Initially, colour film was much grainier than black and white, further limiting the resolution of historic colour aerial photographs. Also, because of potential variation in scale across an aerial photograph owing to distortion, information on historic stream condition is of greatest value when taken from a relatively small area of any given photograph.
Aerial photographs, dating from as early as 1917, have been used to demonstrate and date fluvial changes, along with the land-use changes that were responsible for those stream changes. The general coverage of stereographic aerial photography in the US dates from 1937 to 1938, but limited coverage exists from ca 1925. Stream and valley aggradations are difficult to detect on aerial photographs, but some attendant effects, such as the creation of backswamps and vegetational changes, can be seen and measured. On upland areas, aerial photographs can be used to quantify land use and consequent erosion.

Ground-based oblique photography has been used to date geomorphological processes dating back well into the nineteenth century. The 1940 photograph in figure 8 shows a typical tributary; note the eroded, shallow channel composed of gravel and cobbles, with coarse sediment deposited by overflows on the floodplain. Such tributaries were described as resembling gravel roads. The scene was photographed again in 1974. The stream channel is now narrower, smaller
Figure 8. Oblique ground photographs showing improvement of tributary streams in Vernon County, Wisconsin: (a) 1940 and (b) 1974. Reproduced from Trimble & Crosson [25].

and more stable. The coarse sediment has been covered with fine material, and the floodplain is vegetated to the edge of the stream. This condition has continued and improved over the past 30 years [25]. Although not as systematically available as aerial photography, ground-based photography has existed longer and generally offers better scale and resolution for time-lapse comparisons.

Many major repositories of such photographs include museums, libraries and private holdings; the Library of Congress maintains a national digital library from more than 100 historical collections. In some cases, photogrammetric techniques can also be used with oblique photography, making it possible to obtain precise measurements. Local residents may also have photographed the stream. These photographs offer the advantage of potentially being relatively large in scale in

Phil. Trans. R. Soc. A (2012)
comparison with contemporary maps and historic aerial photographs, and they can provide detailed local information, including stream corridor character and human activities and land use. Streams in long-settled areas or areas with major historic flooding events or other natural disasters impacting people may have been described in historic accounts.

4. Soil erosion

Besides their application to studies of climate fluctuations, neotectonics and archaeology [26–28], short-term river chronologies have a crucial role to play in the assessment of soil erosion as regards its genesis, and changing severity, the extent to which stems from human activities, and the success of measures designed to curb it.

Several decades of field study in Coon Valley, Wisconsin, have yielded findings that bear on all three issues. The basin, which measures $376 \times 10^6$ m$^2$, became the USA’s first watershed conservation project in 1933 and its integrated management was celebrated by Leopold [29]. Progress has been monitored in a variety of ways, notably the resurvey during 1974–1979 of 120 cross sections that were first measured in 1938, and the calculation of its sediment budget since 1939 ([30]; figure 9). In addition, buried soil profiles, sedimentary sequences and man-made structures were excavated and a number of new profiles were surveyed.

The remedial measures taken in the 1930s included terracing, contour strip cropping, gully damming, streambank protection, crop rotation, tree planting and the erection of fences to confine cattle. As shown in figure 10, the changes were not monotonic, but the rapid increase in land being farmed since about 1850 began to be stabilized in about 1900. Erosion and sedimentation rates declined significantly. By 1975, they had fallen in the uplands to about a quarter of those in 1934. Climatic change did not appear to be a factor in these trends [15]. Indeed, to judge from the data in figure 1, between 1920 and 1975, there was a slight rise in mean annual precipitation, and a corresponding increase in storms exceeding 2.5 in (63.5 mm) of rainfall in 24 h. In other words, one might have expected a relapse.

Figure 11 shows that sedimentation in different parts of the Coon Basin peaked in about 1930 and fell rapidly in the next two decades. The measured sections show that the resulting valley fills were being trenched by the 1920s and 1930s. Of course, sedimentation rate is a reliable measure of upland erosion only if there has been no significant change in sediment storage. In Coon Creek, much of the sediment released by human activity in the period of record has gone into floodplain storage, and less than 7 per cent left the basin, but by the 1940s and 1950s, some of the stored sediment was becoming mobile [31].

The remarkable decrease in drainage density in upper Coon Creek (figure 12) between 1938 and 1978 was undoubtedly occasioned by a combination of positive conservation and a decline in erosive farming. It accounts for a general reduction in flood peaks. Unusual storms, such as the floods of at least 100 year magnitude recorded in 1975–1993 [30], could have initiated downcutting without necessarily representing a general trend; but the main source of sediment removal was bank erosion.
1853–1938

- Sources:
  - Tributaries: 42
  - Upland gullies: 73
  - Sheet and rill erosion: 326

- Sinks:
  - Lower main valley: 209
  - Upper main valley: 71
  - Tributary valleys: 87
  - Upland valleys: 38

1938–1975

- Sources:
  - Tributaries: 35
  - Upland gullies: 64
  - Sheet and rill erosion: 114

- Sinks:
  - Lower main valley: 139
  - Upper main valley: 27
  - Upland valleys: 38

1975–1993

- Sources:
  - Tributaries: 9
  - Upland gullies: 19
  - Sheet and rill erosion: 76

- Sinks:
  - Lower main valley: 51
  - Upper main valley: 4
  - Tributaries: 25

Figure 9. Sediment budgets for Coon Creek, Wisconsin, 1853–1993, a basin with an area of 360 km$^2$. Numbers are annual averages for the periods in 10$^3$ metric tonnes yr$^{-1}$. The lower main valley and tributaries are sediment sinks, whereas the upper main valley has been a sediment source. Reproduced from Fraczek [32].

In the southern Piedmont, erosion was apparently negligible in pre-settlement times, but what there was stemmed from Indian agriculture, as well as from forest fires and natural processes [14]. European settlement resulted in erosive land use, which increased between 1700 and 1860 and peaked in 1860–1920. Gully incision fed aggradation of the trunk streams (figure 2) and rising groundwater promoted flooding and the development of backswamps. The decline in agriculture after 1920, with increases in pasture and forest and the adoption of soil conservation measures, generally reduced the incidence of erosion, but incision of some headwaters and bank erosion continued to sustain sedimentation.

Phil. Trans. R. Soc. A (2012)
Figure 10. Changes in land use in Coon Creek during 1850–1975. (Online version in colour.)

Figure 11. Sediment deposition rates (tonnes km$^{-2}$ yr$^{-1}$) based partially on topographic surveys at three valley sites in Coon Creek Basin during 1853–1977.
and sediment migration further downstream. At one location, Mauldin’s milldam, aggradation by 16 feet (4.9 m) was followed by degradation by 7 feet (2.1 m) during 1930–1970.

Any attempt at stream restoration requires some knowledge of conditions before as well as during the historical period to ensure effective watershed management, and this presupposes that the sources are a dependable guide to former conditions (cf. figure 6). Some Australian rivers commonly thought to have been radically transformed by human action can be shown to have changed relatively little, and those changes may have had more natural than human causation [33]. Selecting a stream shape from a photograph and trying to replicate that shape ignores other factors that control the planform and other attributes of the stream and its corridor, including the riparian area. Photographs of streams typically focus on crossings, easily accessible points and cross sections. Yet, little can be learned about the historical pattern and diversity of riparian vegetation from photographs at such locations. Dynamic changes in timing, frequency and magnitude of flows, and sediment load and transport are not revealed in photographs. The size, shape and other physical characteristics of alluvial streams are a function of the types and quantities of sediment in the water and comprising the bed and banks, as well as the nature of the flow conditions. A photograph could easily show a transition phase between two relatively stable states, and may provide little understanding about the direction or magnitude of that change.

In a physical and possibly biological sense, streams are disturbance-driven systems. The current processes that can be observed in a stream channel were shaped by prior floods, sediment input and transport events, channel changes, vegetation changes and species interactions. Although it is useful to think of a stream as having a most probable form, each of these extreme events may reset or alter that form. The historical record may go some way towards revealing these complex relationships.

I thank Claudio Vita-Finzi for his comments on the original draft of this paper.
References


Phil. Trans. R. Soc. A (2012)
32 Fraczek, W. A. 1987 Assessment of the effects of changes in agricultural practices on the magnitude of floods in Coon Creek watershed using hydrograph analysis and air photo interpretation. Unpublished thesis, University Wisconsin, Madison, USA.